

Amendmend to the Specification

[0018] The present inventions specifically addresses and alleviates the above-mentioned deficiencies associated with the prior art. More particularly, the present invention comprises an interleaver comprising a birefringent element device assembly and a reflector configured so as to direct light from the birefringent element device assembly back through the birefringent element device assembly. The birefringent element device assembly comprises at least one spatial birefringent element device. Such spatial birefringent element device utilizes a difference in optical path length caused by a difference in physical path lengths or a difference in refraction indices along different paths, rather than utilizing birefringent crystals.

[0019] Directing light from the birefringent element device assembly back into and through the birefringent element device assembly substantially mitigates crosstalk and/or dispersion. By mitigating crosstalk and dispersion, interleavers having narrower channel spacings may be constructed. As discussed above, narrower interleaver channel spacing facilitates enhanced bandwidth utilization and an desirably increased number of channel counts.

[0023] FIGS. 2a and 2b are schematic diagrams showing the optical beams states and the quarter-wave and half-wave waveplate orientations at different locations for an exemplary two-element fold interleaver of FIG. 1 which has equivalent birefringent element orientation angles of 45° and -15° and birefringent phase delays of Γ and 2Γ , respectively, for the two spatial birefringent element device.

[0031] FIGS. 10a and 10b are schematic diagrams showing the optical beams states and the quarter-wave and half-wave waveplate orientations at different locations for an exemplary the three-element birefringent fold interleaver of FIG. 9 which has equivalent birefringent element orientation angles of 45°, -21° and 7° and birefringent phase delays of Γ , 2Γ and 2Γ , respectively, for the three spatial birefringent element device;

[0043] Two different reference systems are used in this patent application for the determination of angular orientations. One reference system is used for the determination of the equivalent angular orientations of spatial birefringent elements devices, with respect to an equivalent polarization direction of input light. Another reference system is used for the determination of the angular orientations of waveplates with respect to a moving (x, y, z) coordinate system. Thus, when reading the detailed description below, it will be very helpful to understand these two reference systems.

[0045] If there is a series of spatial birefringent elements devices, such as in a birefringent filter, the equivalent angular orientations of each of the elements devices of the filter are measured by their fast axes with respect to an equivalent polarization direction of incoming light just prior to the incoming light reaching the first birefringent element device of the filter. If there are more than one birefringent filters in a sequence, then the equivalent angular orientations are determined separately for each birefringent filter (the equivalent angular orientations are measured with respect to an corresponding equivalent polarization direction of incoming light just prior to the incoming light reaching the first birefringent element device of each different filter). Thus, each birefringent filter has its own independent reference for the determination of the angular orientations of the birefringent elements devices thereof. Each spatial birefringent element device has its own equivalent polarization direction of incoming light just prior to the incoming light reaching the first birefringent element device.

[0048] The present invention comprises an interleaver which comprises a birefringent element device assembly. The birefringent element device assembly comprises at least one spatial birefringent element device. A reflector is configured so as to direct light which is emitted from the birefringent element

device assembly back into and through the birefringent element device assembly, such that the light travels through the birefringent element device assembly in two different, generally opposite directions. The birefringent element device assembly provides two output components of the light input thereto. One output component corresponds to the interleaved odd channels and the other corresponds to the interleaved even channels. The reflector is configured to direct the two components back through the birefringent element device assembly. By transmitting the light through the birefringent element assembly in both directions, crosstalk can be substantially mitigated. Further, dispersion can be substantially mitigated or eliminated.

[0049] Directing light from the birefringent element device assembly back into and through the birefringent element device assembly is achieved by use of an optical reflector. The reflector preferably comprises a single prism. However, those skilled in the art will appreciate that the reflector may alternatively comprise more than one prism and/or one or more mirrors or etalons.

[0050] The birefringent element device assembly may contain any desired number of spatial birefringent elements devices. For example, the birefringent element device assembly may contain one, two, three, four, five or more spatial birefringent elements devices. As those skilled in the art will appreciate, additional birefringent elements devices tend to enhance the transmission vs. wavelength curve of the birefringent filter or interleaver defined by the birefringent elements devices, so as to tend to provide a flatter and wider passband and/or so as to provide a deeper and wider stopband.

[0051] According to one preferred embodiment of the present invention, the birefringent element device assembly is disposed intermediate (in an optical sense) an input polarization beam displacer and an intermediate polarization beam displacer.

[0052] The birefringent element device assembly comprises at least one spatial birefringent element device. The spatial birefringent element device physically separate two orthogonally polarized optical beams and provides differences in physical path lengths and/or refraction indices for the two optical beams so as to provide a birefringent effect. In this manner, the use of birefringent crystals and disadvantages commonly associated therewith are eliminated.

[0053] According to one preferred embodiment of the present invention, the interleaver comprises an input polarization beam displacer from which light is transmitted to the birefringent element device assembly; a first input half-wave waveplate assembly configured to receive light from the input polarization beam displacer and control the light polarization directions; an intermediate polarization beam displacer configured to transmit light from the birefringent element device assembly before the light is transmitted back through the birefringent element device assembly; a second input half-wave waveplate assembly configured to control the light polarization directions before the light is transmitted back through the birefringent element device assembly; an output half-wave waveplate assembly configured to control the light polarization directions after the light is transmitted back through the birefringent element device assembly; and an output polarization beam displacer to which light is transmitted after the light has been transmitted back through the birefringent element device assembly.

[0054] The spatial birefringent element device preferably comprises a polarization beam splitter (which separates an optical beam into two orthogonally polarized optical components); a first mirror; a second mirror; first quarter-wave waveplate(s) having an optic axis thereof oriented at an angle of approximately 45° with respect to the +x axis at that location, the first quarter-wave waveplate(s) being disposed intermediate the polarization beam splitter and the first mirror; second quarter-wave waveplate(s) having an optic axis thereof oriented at an angle of approximately 45° with respect to the +x axis at that location, the second quarter-wave waveplate(s) being disposed intermediate the polarization beam splitter and the second mirror.

[0055] According to the present invention, a birefringent effect is obtained by defining a first and a second light paths at each birefringent element device, wherein light input into the birefringent element device is split into two composite beams, each of the two composite beams travels along separate paths. The two paths have different optical path lengths, such that when the two beams recombine a birefringent effect is achieved. Preferably, the splitting of light into two components and the recombining of the two components are achieved utilizing a polarization beam splitter. Those skilled in the art will appreciate that various other devices for separating and recombining light (such as polarization beam displacers) are likewise suitable. Reflectors, such as mirrors, or prisms, can be used to define the two paths. Generally, each path will be from a polarization beam splitter to a mirror or prism and back to the polarization beam splitter. Different optical path lengths between the two paths may be obtained by defining the two paths so as to have different physical path lengths or by inserting a material having a different refraction index into one of the two paths, so as to cause the two paths to have different optical path lengths. However, those skilled in the art will appreciate that various other means for defining two paths having different optical path lengths are likewise suitable.

[0056] Half-wave waveplates are used to control the light polarization direction before light enters a polarization beam splitter, so as to define a desired angle between input light polarization direction and the fast axis of the spatial birefringent element device, which further defines an equivalent angle for birefringent element device orientation. The fast axis is usually along x-axis or y-axis, which is determined by the configuration of spatial birefringent element device using a polarization beam splitter. The equivalent angle is the angle which would be utilized in a birefringent filter having birefringent crystals in order to obtain the same effect. That is, the equivalent angle of a speeial spatial birefringent element device according to the present invention is the angle between the fast axis of a birefringent crystal and the polarization direction of light input thereto which would be required in order to obtain the same optical effect that the spatial birefringent device of the present invention provides.

[0057] When more than one spatial birefringent element device is utilized, then one or more half-waveplates are typically disposed between two adjacent polarization beam splitters, so as to control the light polarization direction before light entering each subsequent polarization beam splitter in order to define the equivalent angle.

[0058] Thus, the half-wave waveplates which light passes through prior to entering the polarization beam splitter of the present invention define the transmission characteristics (e.g., cross-talk) of the birefringent element device assembly.

[0059] As discussed above, a half-wave waveplate is used to define the equivalent orientation angle for each birefringent element device of the present invention. It is worthwhile to note that the equivalent orientation angle is controlled by manipulating the polarization direction of light input to the polarization beam splitter of each birefringent element device. At the beam split point of the polarization beam splitter, the polarization direction of light which travels along the shorter of the two paths is the fast axis of the spatial birefringent element device. Beyond the beam split point, the polarization directions of light traveling along the short path and the long path are manipulated so as to cause that light to be either transmitted or reflected again by the polarization beam splitter, such that the light from the two paths recombines and is transmitted in the desired direction (such as to the next birefringent element device). Therefore, the polarization direction of light input to each birefringent element device must be manipulated so as to obtain the desired equivalent angle. Manipulation of the polarization of light input to a birefringent element device is accomplished by rotating the polarization direction of light input to a birefringent element device by the desired amount utilizing a half-wave waveplate.

[0061] The present invention thus comprises a method for interleaving, wherein the method comprises

transmitting light through a birefringent element device assembly in a first direction and then transmitting the light through the same birefringent element device assembly in a second direction. The birefringent element device assembly comprises at least one spatial birefringent element device and the spatial birefringent element device causes a first beam of light to travel along a first path and causes a second beam of light to travel along a second path. The first and second beams of light are preferably generally orthogonal with respect to one another. The first and second paths have different optical path lengths with respect to one another. The different optical paths length may be formed by either providing different physical path lengths or by providing materials having different refraction indices along the first and second paths. Before the light enters the birefringent element device, its polarization direction is manipulated and controlled so as to obtain a desired equivalent angle for birefringent element device orientation.

[0064] Transmitting the light through the birefringent element device assembly in both the first and the second directions mitigates crosstalk. Further, dispersion can be mitigated in interleavers having more than one spatial birefringent element device.

[0068] However, according to the present invention, an interleaver utilizing a birefringent filter is constructed in a manner which substantially mitigates crosstalk without additional birefringent elements devices. Further, dispersion can be substantially mitigated and eliminated without additional birefringent elements devices. This is accomplished by configuring the present invention such that light travels through the same birefringent filter twice or more times, in two generally opposite directions. Therefore, the present invention facilitates the construction of an interleaver which makes possible substantially reduced channel spacing, so as to desirably increase the effective bandwidth of an optical medium and thereby enhance the potential for channel count increases.

[0070] In a birefringent filter, if φ_1 , φ_2 , and φ_3 are the orientation angles for the first, second and third birefringent elements devices, then the same transmission performance is obtained for birefringent element device orientations of $90^\circ - \varphi_1$, $90^\circ - \varphi_2$ and $90^\circ - \varphi_3$, as well as for birefringent element device orientations of $90^\circ + \varphi_1$, $90^\circ + \varphi_2$ and $90^\circ + \varphi_3$, respectively. However, the dispersion curves are flipped about the zero dispersion axis for the sets of angles of $90^\circ - \varphi_1$, $90^\circ - \varphi_2$ and $90^\circ - \varphi_3$, as well as $90^\circ + \varphi_1$, $90^\circ + \varphi_2$ and $90^\circ + \varphi_3$, when taken with respect to the orientations of φ_1 , φ_2 and φ_3 . That is, the dispersion curve of a birefringent filter having birefringent element device orientations of φ_1 , φ_2 and φ_3 will be opposite to the dispersion curve of either a birefringent filter having birefringent element orientations of $90^\circ - \varphi_1$, $90^\circ - \varphi_2$ and $90^\circ - \varphi_3$ or a birefringent filter having birefringent element device orientations of $90^\circ + \varphi_1$, $90^\circ + \varphi_2$ and $90^\circ + \varphi_3$. This is true when the phase delays of the first, second and third birefringent elements devices are in the same order.

[0071] It is possible to configure two birefringent element device assemblies such that the birefringent elements devices thereof have phase delays which are and reverse order with respect to one another and wherein the dispersion curves for the two birefringent element device assemblies are opposite to one another. It has been found that if φ_1 , φ_2 , and φ_3 are the orientation angles for the first, second and third birefringent elements devices having a first order of phase delays, then the same transmission performance is obtained for birefringent elements devices orientations of $90^\circ - \varphi_3$, $90^\circ - \varphi_2$, and $90^\circ - \varphi_1$ or $90^\circ + \varphi_3$, $90^\circ + \varphi_2$ and $90^\circ + \varphi_1$ for a parallel component from the birefringent element device assembly having angles of φ_1 , φ_2 , and φ_3 , as well as for birefringent element device orientations of φ_3 , φ_2 and φ_1 or $-\varphi_3$, $-\varphi_2$ and $-\varphi_1$ for an orthogonal component from the birefringent element device assembly having angle orientations of φ_1 , φ_2 , and φ_3 . Again, the dispersion curves are flipped about the zero dispersion axis for these sets of angles with respect to the orientations of φ_1 , φ_2 and φ_3 .

[0072] Thus, two different birefringent element device assemblies may be constructed so as to substantially cancel the dispersion introduced by one another when either the order of the phase delays of each birefringent element device assembly is the same or when the order of the phase delays of each birefringent element device assembly are reversed with respect to one another.

[0074] Dispersion can be substantially mitigated by transmitting an optical beam through a birefringent element device assembly, such as a birefringent element device assembly comprising three different birefringent elements devices, wherein the first element device has a fast axis oriented at an angle of φ_1 , a second birefringent element device has a fast axis thereof oriented at an angle of φ_2 , and a third birefringent element device has a fast axis thereof oriented at an angle of φ_3 , all with respect to the polarization direction of the input. After the optical beam passes through the three birefringent elements devices, two separate sets of interleaved signals (odd channels and even channels) having polarizations which are orthogonal to one another are obtained. Then, the incident light is reflected, such as by a mirror or prism, and then travels back through the same set of birefringent elements devices in the reverse direction. Before the light travels back through the same set of birefringent elements devices in the reverse direction, the polarization directions of the odd channels and the even channels are aligned such that the angular orientation of the birefringent elements devices are $90^\circ - \varphi_3$, $90^\circ - \varphi_2$, $90^\circ - \varphi_1$ or $90^\circ + \varphi_3$, $90^\circ + \varphi_2$, $90^\circ + \varphi_1$ with respect to the input polarization direction of the returning light of the parallel component and $-\varphi_3$, $-\varphi_2$, $-\varphi_1$ or φ_3 , φ_2 , φ_1 with respect to the input polarization direction of the returning light of the orthogonal component.

[0075] When light travels through a birefringent assembly in the first direction, the birefringent element device angles are φ_1 , φ_2 , φ_3 , and when light travels through the same birefringent element device assembly in the reverse direction, the birefringent element device angles are $90^\circ - \varphi_3$, $90^\circ - \varphi_2$, $90^\circ - \varphi_1$, or $90^\circ + \varphi_3$, $90^\circ + \varphi_2$, $90^\circ + \varphi_1$ for the parallel component and $-\varphi_3$, $-\varphi_2$, $-\varphi_1$ or φ_3 , φ_2 , φ_1 for the orthogonal component in the order in which light encounters the birefringent elements devices. Thus, it is possible to construct an interleaver which provides zero or approximately zero dispersion and which does not require the use of two separate birefringent filters, as discussed above. Such a zero dispersion interleaver may be constructed by folding the light path, such that incident light traveling through the birefringent filter in a forward direction is reflected back through the filter in a reverse direction.

[0076] Referring now to FIG. 1, a two-element birefringent filter or interleaver having a fold configuration according to one embodiment of the present invention is shown. The fold interleavers of the present invention provide low cross-talk and/or zero or very low dispersion by directing light which passes through a birefringent element device assembly thereof back through the same birefringent element device assembly in a direction opposite to the direction in which the light was first transmitted through the birefringent element device assembly. In this manner, dispersion introduced into the light during its first pass through the birefringent element device assembly is compensated for or cancelled during its second pass through the birefringent element device assembly. That is, when light passes through the birefringent element device assembly in the first direction, a first dispersion vs. wavelength curve results and when light passes through the birefringent element device assembly in a second direction, generally opposite to the first direction, a second dispersion vs. wavelength curve results which is flipped or generally opposite to the first dispersion vs. wavelength curve, thus, result in a net dispersion resulting from both passes through the birefringent element device assembly of zero or approximately zero dispersion. Since light travels through the birefringent element device assembly twice (once in a first or forward direction and again in the second or reverse direction) the transmission characteristics of the interleaver are enhanced with respect to the transmission characteristics of light which passes through such an interleaver only once (such as in the forward direction only). Such enhanced transmission characteristics improve cross-talk.

[0077] Indeed, light may be transmitted through the birefringent element device of the assembly of the present invention any desired number of times, so as to provide the desired transmission characteristics. As those skilled in the art will appreciate, transmitting light through the birefringent element device assembly of the present invention an even number of times results in zero or nearly zero dispersion, since the dispersion introduced during transmission through the birefringent element device assembly in one direction is substantially canceled by dispersion introduced during transmission through the birefringent element device assembly in the opposite direction. However, if the dispersion characteristics of the interleaver are not important, then light may be transmitted through the birefringent element device assembly an odd number of times.

[0079] Referring now to FIGS. 2a and 2b, the optical beam states and the quarter-wave and half-wave waveplate orientations at various locations for an exemplary two-element fold interleaver of FIG. 1 are shown. The waveplates orientation shown in FIGS. 2a and 2b are such that they provide birefringent element device orientations equivalent to the birefringent crystal orientations of 45° and -15° and provide phase delays which are equivalent to birefringent crystals of phase delays Γ and 2Γ , respectively. In FIGS. 2a and 2b, each of the four boxes correspond to a physical beam position at various locations. The polarization beam displacers 10, 11 and 18 shift the optical beams to these various beam positions according to the orientation of polarization beam displacer and the optical beam polarization. The optic axis orientation angles of the quarter-wave and half-wave waveplates shown in FIGS. 2a and 2b are referred to the +x axis at the corresponding locations. The birefringent effect derived by each spatial birefringent element device of the birefringent element device assembly 12 is determined by the distance difference between the polarization beam splitter and the mirrors thereof. The birefringent phase delay (difference) between the two corresponding components is Γ_1 for element device one and Γ_2 for element device two, respectively, according to the formula:

$$\Gamma_1 = 2 \cdot (L_1 - L_2) \cdot 2\pi / \lambda = L \cdot 2\pi / \lambda = \Gamma$$

$$\Gamma_2 = 2 \cdot (L_3 - L_4) \cdot 2\pi / \lambda = 2L \cdot 2\pi / \lambda = 2\Gamma$$

Where λ is the optical wavelength.

[0081] The polarization beam splitter 19a, the quarter-wave waveplate 23a, the mirror 14a, the quarter-wave waveplate 22a, the mirror 15a and the half-wave waveplates 30 define a portion of the first birefringent element device of the birefringent element device assembly 12. An input polarization beam displacer 10 provide light to half-wave waveplates 30 from which the light is transmitted into polarization beam splitter 19a. The input polarization beam displacer 10 separates light input to the interleaver into two optical beams having known polarization directions, such that the polarization directions of the two optical beams can be controlled (such as by a half-wave waveplate) to define the desired equivalent birefringent element device orientation angles. As mentioned above, if polarized light having a known polarization direction is provided to the interleaver, then the input beam displacer 10 may be eliminated (and the two composite beams resulting therefrom will be reduced to a single beam).

[0082] Polarization beam splitter 19a separates an optical beam into two components. The first component having polarization direction along x-axis is transmitted straight there through to quarter-wave waveplate 23a and mirror 14a. Mirror 14a reflects the light back through quarter-wave waveplate 23a and into polarization beam splitter 19a. The second component of the light having a polarization generally orthogonal to the first component (along y-axis) is deflected by polarization beam splitter 19a through quarter-wave waveplate 22a and is reflect by mirror 15a back through polarization beam splitter 19a. The polarization direction of the first component is changed by 90° by the combination of the mirror and the

quarter-wave waveplate 23a, (having an optical axis thereof oriented at 45° with respect to the +x axis), so that the first component is reflected by the polarization beam splitter 19a to location 10 when the first component is transmitted back to the polarization beam splitter 19a. In a similar manner, the polarization direction of the second component is changed by 90° by the cooperation of the mirror and the quarter-wave waveplate 22a (having an optical axis thereof oriented at 45° with respect to the +x axis), so that it is transmitted through the polarization beam splitter 19a to location 10 when it is transmitted back to the polarization beam splitter 19a. The first and second components are together at location 10. Light from the polarization beam splitter 19a is transmitted to a second birefringent element device of the birefringent element device assembly 12 which comprises half-wave waveplates 33a, a polarization beam splitter 19b, quarter-wave waveplate 23b, mirror 14b, quarter-wave waveplate 21b and mirror 15b, all of which operate in a manner analogous to the corresponding components of the first birefringent element. Thus, the birefringent element device assembly comprises two elements, as shown in FIG. 1. The quarter-wave waveplates 21a, 22a, 23a, 24a, 21b, 22b, 23b and 24b orient light returning from the mirrors so that the light is either transmitted through or reflected by the corresponding polarization beam splitter and the two components recombine. For example, quarter-wave waveplate 22a orients the polarization direction of light from mirror 15a such that that component of the light is transmitted through the polarization beam splitter 19a and quarter-wave waveplate 23a orients the polarization direction of light from mirror 14a such that light from mirror 14a is reflected by the polarization beam splitter 19a to location 10.

[0083] The polarization beam splitters (such as 19a and 19b of FIG. 1 and 19a, 19b, and 19c of FIG. 9) may comprise either single polarization beam splitters as shown, or may alternatively comprise multiple polarization beam splitters. For example, separate polarization beam splitters may be utilized at each point where light is separated and recombined, thereby replacing each polarization beam splitter shown in FIG. 1 or FIG. 9 with four separate polarization beam splitters. As a further alternative, each polarization beam splitter shown in FIG. 1 and FIG. 9 may be replaced with two polarization beam splitters, wherein one polarization beam splitter splits and recombines light traveling in the forward direction through the birefringent element device assembly and the other polarization beam splitter separates and combines the light traveling in the opposite direction (back through the birefringent element device assembly).

[0084] As shown in FIG. 1, distance L_1 and distance L_2 are different with respect to one another, so as to provide the desired phase delay and the consequent birefringent effect. Similarly, distances L_3 and L_4 of the second birefringent element device are different, again so as to provide the desired phase delay and the consequent birefringent effect for the second birefringent element device.

[0085] Half-wave waveplates 30 and 33a are used to manipulate the input light polarization directions for desired equivalent birefringent element orientation angles ϕ_1 and ϕ_2 , respectively. After exiting the birefringent element device assembly 12, light from the polarization beam splitter 19b is transmitted through half-wave waveplate 34 to prism 13. After the light has been transmitted through half-wave waveplate 34 and polarization beam displacer 18, then the light has effectively passed through an interleaver. Transmitting the light back through the birefringent element device assembly 12 effectively causes the light to pass through another interleaver having equivalent birefringent element device orientation angles for zero dispersion, which are determined by the orientation of half-wave waveplates 35 and 32a. Thus, enhanced transmission characteristics and mitigated (nearly zero) dispersion can be obtained. In effect, the input light provided to the interleaver of FIG. 1 passes through two interleavers wherein the first interleaver introduces dispersion and the second interleaver (which comprises the same physical components as the first interleaver) introduces substantially the opposite dispersion, such that the dispersion of the first interleaver and the dispersion of the second interleaver substantially cancel one another.

[0087] Thus, after light has passed through half-wave waveplate 34 and intermediate beam displacer 18, the light has been separated into odd and even channels. Prism 13 deflects light through polarization beam

displacer 18 and back into the birefringent element device assembly 12 where the light passes through half-wave waveplates 35, polarization beam splitter 19b, quarter-wave waveplate 24b, quarter-wave waveplate 22b, half-wave waveplate 32a, quarter-wave waveplate 24a, and quarter-wave waveplate 21a, while being reflected by mirrors 14a, 14b, 15a and 15b in a manner analogous to the manner in which light is transmitted through birefringent element device assembly 12 in the first direction.

[0088] Light which has been transmitted back through the birefringent element device assembly 12 as transmitted through half-wave waveplates 31 and output polarization beam displacer 11 so as to form two light beams, one of which contains the odd channels and the other contains the even channels.

[0089] When only two birefringent elements devices are utilized, then the order of the birefringent elements devices is not important. That is, if a first equivalent angle and first phase delay is associated with the first birefringent element device and a second equivalent angle and second phase delay associated with the second birefringent element device, an equivalent interleaver is constructed by making the first birefringent element device have the second equivalent angle and the second phase delay and making the second birefringent element device have the first equivalent angle and the first phase delay.

[0097] Preferably, the phase delay for the second spatial birefringent element device and the third spatial birefringent element device of the three-element interleaver are twice that of the first spatial birefringent element device $\Gamma_1 = L \cdot 2\pi / \lambda$, $\Gamma_2 = \Gamma_3 = 2L \cdot 2\pi / \lambda$. The channel spacing is determined by the phase delay of the first element device (Γ_1). The half-wave waveplates at various locations in the apparatus are controlled to ensure that the optical beams are polarized along the appropriate direction so that the desired passband and stopband characteristics are obtained. In Fig. 10b, The two output beams 1" and 2" (odd channels) and 3" and 4" (even channels) are the two series of interleaved channels of having zero or nearly zero dispersion.

[0098] When three birefringent elements devices are utilized, as shown in FIG. 9, then the equivalent angle and phase delay associated with the first birefringent element device may be swapped with the equivalent angle and phase delay associated with the third birefringent element device. That is, for a first birefringent element device having a first equivalent angle and a first phase delay and a third birefringent element device having a third equivalent angle and a third phase delay, then equivalent performance is obtained when the first birefringent element device has the third equivalent angle and the third phase delay and the third birefringent element device has the first equivalent angle and the first phase delay.

[0099] Referring now to FIG. 11, the dispersion vs. wavelength for the three-element device fold interleaver of FIGS. 9, 10a and 10b for one of the interleaved channels is shown. The dispersion is zero or approximately zero for all wavelengths.

[0101] Referring now to FIG. 14, the dispersion vs. wavelength for a non-fold interleaver having equivalent birefringent element device orientation of 45°, -21° and 7° and having phase delays of Γ , 2Γ and 2Γ is shown. It is clear that the dispersion for the non-fold three-element device interleaver shown in FIG. 14 is substantially greater than the dispersion for the three-element device fold interleaver shown in FIG. 11.

[0104] Referring now to FIGS. 17 and 18, alternative layout configurations for two-element device fold interleaver and the three-element device fold interleavers are shown. The waveplates are omitted for clarity.

[0107] Other configurations are possible according to the present invention, for example Table I below summarizes the first stage phase delays, first stage orientations, second stage phase delays, and second

stage orientations for possible embodiment of present invention. As discussed in detail below, it should be noted that the first stage is comprised of the spatial birefringent element device assembly when light passes therethrough in one direction and the second stage is comprised generally of the same birefringent element device assembly when light passes therethrough in the opposite direction.

Table I

First Stage <u>Phase Delays</u>	First Stage <u>Orientations</u>	Second Stage <u>Phase Delays</u>	Second Stage <u>Orientations</u>
$\Gamma + 2m_1 \pi$, $2\Gamma + 2m_2 \pi$, $2\Gamma + 2m_3 \pi$	$\varphi_1, \varphi_2, \varphi_3$	$2\Gamma' + 2k_3 \pi$, $2\Gamma' + 2k_2 \pi$, $\Gamma' + 2k_1 \pi$	$90^\circ \pm \varphi_3, 90^\circ \pm \varphi_2, 90^\circ \pm \varphi_1$ (parallel component) $\pm \varphi_3, \pm \varphi_2, \pm \varphi_1$ (orthogonal component) where $\Gamma - \Gamma' = 2l\pi$
$\Gamma + 2m_1 \pi$, $2\Gamma + 2m_2 \pi$, $2\Gamma + 2m_3 \pi$	$\varphi_1, \varphi_2, \varphi_3$	$2\Gamma' + 2k_3 \pi$, $2\Gamma' + 2k_2 \pi$, $\Gamma' + 2k_1 \pi$	$90^\circ \pm \varphi_3, 90^\circ \pm \varphi_2, 90^\circ \pm \varphi_1$ (parallel component) $\pm \varphi_3, \pm \varphi_2, \pm \varphi_1$ (orthogonal component) where $\Gamma - \Gamma' = (2l + 1)\pi$
$2\Gamma + 2m_3 \pi$, $2\Gamma + 2m_2 \pi$, $\Gamma + 2m_1 \pi$	$\varphi_3, \varphi_2, \varphi_1$	$\Gamma' + 2k_1 \pi$, $2\Gamma' + 2k_2 \pi$, $2\Gamma' + 2k_3 \pi$	$90^\circ \pm \varphi_1, 90^\circ \pm \varphi_2, 90^\circ \pm \varphi_3$ (parallel component) $\pm \varphi_1, \pm \varphi_2, \pm \varphi_3$ (orthogonal component) where $\Gamma - \Gamma' = 2l\pi$
$2\Gamma + 2m_3 \pi$, $2\Gamma + 2m_2 \pi$, $\Gamma + 2m_1 \pi$	$\varphi_3, \varphi_2, \varphi_1$	$\Gamma' + 2k_1 \pi$, $2\Gamma' + 2k_2 \pi$, $2\Gamma' + 2k_3 \pi$	$\pm \varphi_1, \pm \varphi_2, \pm \varphi_3$ (parallel component) $90^\circ \pm \varphi_1, 90^\circ \pm \varphi_2, 90^\circ \pm \varphi_3$ (orthogonal component) where $\Gamma - \Gamma' = (2l + 1)\pi$

Wherein $m_1, m_2, m_3, k_1, k_2, k_3$ and l are integers $(0, \pm 1, \pm 2, \dots)$.

[0108] The fourth column of Table I (entitled Second Stage Orientations) shows four sets of birefringent element device orientations for each configuration. Two sets of angles for the parallel component are provided and two sets of angles for the orthogonal component are provided.

[0110] Light from the birefringent element device assembly is directed back into the same birefringent element device assembly in a direction which is opposite to that direction in which light first traveled through the birefringent element device assembly. As light travels through the birefringent element device assembly in the first direction, the birefringent element device assembly may be considered as a first stage. When light travels back through the birefringent element device assembly in the second or reverse direction, the birefringent element device assembly may be considered as a second stage. Therefore, the parallel component and the orthogonal component from the first stage are transmitted through birefringent element device of the second stage. It is important to remember that the first and second stages are actually the same birefringent element device assembly, with light being transmitted therethrough in one direction so as to define a first stage of interleaving and light being transmitted therethrough in a second or reverse direction so as to define a second stage of interleaving.

[0111] When the phase delays of the first stage are reversed in order with respect to the phase delays of the second stage, then the parallel component and the orthogonal component are transmitted through birefringent element device having different angular orientations, as also shown in Table I.

[0112] As those skilled in the art will appreciate, transmitting the parallel component and the orthogonal component through birefringent element device having different angular orientations can

be accomplished in various different ways. For example, the parallel component and the orthogonal component may be transmitted through two different sets of birefringent element device (which define the second stage), with each set having angular orientations which are appropriate for that component. Alternatively, polarization rotators (such as half-wave waveplates) may be used to align the parallel component and/or the orthogonal component such that the required orientation angles are provided and only a single set of birefringent element device is required for the second stage.

[0115] In addition to manipulating the angular orientation of birefringent element device in the first and second stages of an interleaver or the like so as to provide approximately zero dispersion, Table I shows that it is also possible to manipulate the phase delays of the birefringent element device so as to provide approximately zero dispersion. Thus, various combinations of angular orientations of the birefringent element device and phase delays thereof may be utilized so as to provide approximately zero dispersion.

[0116] However, it is important to appreciate that when light is transmitted back through the same set of birefringent element device that the light was first transmitted through, such that the light travels through the same set of birefringent element device in two different directions, then the phase delays of the birefringent element device are generally constrained such that the phase delays on the return path are opposite those on the forward path. In a fold interleaver, the delays for both the forward and reverse paths are defined by the phase delays associated with the birefringent element device through which light travels in two different directions. However, since light does not necessarily have to travel through the common set of birefringent element device along precisely the same path in both directions, it may be desirable to insert additional elements into one of the light paths (forward or reverse) and/or otherwise modify the phase delay(s) of one of the paths such that the phase delays along the forward path are not the same of the phase delays along the reverse path.

[0117] Varying the phase delay of the birefringent element device in the first and/or second stages of an interleaver or the like provides added flexibility in the manner in which approximately zero dispersion may be obtained. This added flexibility may be utilized to provide ease in manufacturing and/or reduced assembly costs.

[0118] The different configurations of the present invention, wherein a first stage having three birefringent element device cooperates with a second stage (it is important to remember that the first and second stages preferably comprise a single birefringent element device assembly through which light travels in two different directions) also having three birefringent element device so as to facilitate the construction of a device such as optical interleaver which has approximately zero dispersion, are summarized generally in Table I. This table contains those configurations wherein approximately zero dispersion is obtained by varying the orientation of the birefringent elements of the second stage with respect to those of the first stage, varying the phase delays of the birefringent element device of the first and/or second stage, and by varying both the orientations of the birefringent elements devices of the second stage with respect to the first stage and the phase delays of the first and/or second stage.

[0120] The fold interleavers of the present invention overcome many of the limitations associated with the optical, physical, mechanical and thermal properties of the birefringent crystal. For example, since a spatial distance determines the amount of birefringence obtained in any element of the birefringent element device assembly, variable or tuned birefringence may be obtained by making at least one mirror of an element movable or by facilitating the introduction of different materials, having different indices of refraction, into at least one of the two optical paths of a spatial birefringent

element device. Thus, tunable fold interleaver can be constructed.

[0122] Thus, the fold interleaver of the present invention provides a low cost and small size. It is worthwhile to note that the folded configuration of the interleaver of the present invention provides automatic match between successive stages of birefringent filtering for effective mitigation of crosstalk and/or dispersion. That is, each pass through the birefringent assembly in a direction opposite to the previous pass therethrough apparently occurs through a birefringent element device assembly which is matched to the birefringent element device assembly which the light previously pass through since the light passes through the same birefringent element device assembly in both instances.

[0124] One important aspect of this invention is the ability to control the difference in optical path length between the first and second paths in the spatial birefringent element device, so that the birefringence value provided by this difference in optical path length does not vary undesirably during operation of the invention, such as due to temperature changes.

[0127] According to the present invention, the difference in optical path length between the first and second paths in a spatial birefringent element device may optionally be controlled by inserting a material having desired optical, thermal and/or mechanical properties into at least the longer of the two paths, so as to substantially fix the optical path length which defines the difference between the first and second paths. Thus, by inserting such a material into at least that portion of one path that defines optical path length difference, substantially more stable operation of the devices is achieved.

[0131] It is important to appreciate that, as mentioned above, the phase delay necessary for providing a birefringent effect may be obtained by inserting a material having desired optical, thermal, and/or mechanical properties into at least a portion of either the first or second path in a spatial birefringent element device.